

CALIBRATING STORAGE TANKS FOR SOIL EROSION MEASUREMENT FROM PLOTS

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ABSTRACT

Many plots for soil loss measurements are equipped with a sequence of tanks for measuring runoff volume and sediment concentration. The stored water volume is easily determined by a water depth measurement while the sediment concentration is often measured by collecting samples of the mixed suspension. In this paper, using the Π -theorem of dimensional analysis, the functional relationship describing the mixing of the suspension in the tank is expressed in a dimensionless form. The recognized dimensionless groups allow the establishment, for given soil and water depth in the tank, of the relationship (calibration curve) between the actual and the measured concentration. The calibration curve, using measured concentration values obtained from sampling taps located at different heights on the vertical of a tank wall, is shown to be linear. For a given soil, the slope of the calibration curve is related to the water depth. We also show that the same dimensionless groups allow the deduction of a scale-up procedure and the possibility of using a small tank, similar to the field one, for investigating additional effects neglected in the theoretical analysis. The effects of the following factors on the calibration curve are examined: (1) sampling direction along the vertical, i.e. starting the sampling from the upper tap to the lower one or *vice versa*; (2) mathematical shape of the concentration profile; (3) representativeness of the calibration curve; (4) sampling volume; (5) water depth into the tank (i.e. filling level); (6) suspension mixing time; (7) grain size distribution of the eroded soil particles for given soil type; (8) time between the end of the erosive event and the starting of the sampling procedure (delay time). Finally, an attempt is made to define a simpler sampling procedure based on a single measurement with a dipped sampler. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: soil erosion; plot measurements; sediment concentration; calibration curve

INTRODUCTION

Experimental studies on sheet and rill erosion due to overland flow are generally carried out by plot soil loss measurement. Runoff from a plot bounded by galvanized steel or plastic is collected and carried by a conveyance system (e.g. H-flume or pipe) to a sampling unit. The sampling unit can directly sample runoff for measuring runoff volume and sediment concentration (e.g. Coshocton wheel; Fagna-type unit). The Coshocton wheel (Carter and Parsons, 1967) has a sampling head with a narrow opening cutting across the jet from the flume and collecting a given portion of the runoff which is transported to a storage tank. In the Fagna-type hydrological unit (Bazzoffi, 1993), runoff, cleaned of the coarser material by passing through a sedimentation tank, falls on a revolving pot. For each pot rotation, a few cubic centimetres of the outgoing jet are intercepted by a sampling hole and conveyed to a small tank. This sampling unit allows measurement of the hydrograph by counting the number of rotations and the corresponding time. Both sampling devices need field tests to calibrate the measurement system.

A simple method for measuring the sediment concentration is to store all runoff or to divide it into a sequence of tanks. In each tank, stored water volume is easily determined by a water depth measurement. Sediment concentration can be measured by either catching the whole sediment amount, after siphoning the supernatant cleared water, or collecting a sample of the mixed suspension (Pierson *et al.*, 1994). In the first case, the

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sediment concentration measurement is accurate but it requires the removal of high mud volumes which have to be oven-dried. Therefore, this technique is more and more cumbersome and time-consuming for increasing amounts of collected runoff, and number and size of plots. As a matter of fact, the sample suspended sediment concentration is representative of the whole suspension if it is well mixed, i.e. the suspended concentration C_i assumes the same value in each i measurement point of the tank. Consequently the sediment amount is calculated by multiplying the C_i sample concentration by runoff volume.

Recently, Lang (1992) carried out an experimental study on a clay soil to test a bottle sampler for sampling soil–water mixtures containing 1–187 gl^{-1} of solid particles. The analysis showed that the actual suspended particle concentration was underestimated by a factor of two. The results of the study induced Lang (1992) to throw doubt on the reliability of soil loss data from plots collected using a runoff sampling technique.

Since in many plots the runoff and sediment concentration are sampled manually, Zobisch *et al.* (1996) also verified the accuracy and the repeatability of this sampling procedure by comparing the sampling results of different field workers. The authors showed that runoff volume was slightly underestimated while an unacceptably poor accuracy of soil loss measurement was recognized. Zobisch *et al.* (1996) concluded that the differences were due to the way the suspended sediment was stirred just before sampling and the way the sample was retrieved (by plunging a beaker into the suspension). In fact the thoroughness of mixing of the suspended sediment influences its homogeneity within the tank; moreover, the timing and plunging depth of the sample beaker determine the concentration of suspended sediment.

In this paper, the results of an investigation carried out to determine an accurate manual sampling procedure for measuring the suspended sediment concentration in a runoff–soil loss storage tank are reported. First, using the Π -theorem of dimensional analysis (Barenblatt, 1987), the functional relationship describing the mixing of the suspension into the tank is expressed in a dimensionless form. The recognized dimensionless groups allow a scale-up procedure to be established and the possibility of using a small tank, similar to the field one, for investigating additional effects (mathematical shape of the concentration profile, sampling direction along the vertical, representativeness of a calibration curve, mixing time, etc.) neglected in the theoretical analysis. Finally, an attempt to define a simpler sampling procedure based on a single measurement by a dipped sampler is carried out.

STORAGE TANK CALIBRATING PROCEDURE

When considerable runoff events occur in a soil erosion plot, the most widely applied sampling procedure for the sediment stored in a tank is to mix the whole suspension for a given time and to collect one or several 'representative' suspension samples. These samples are collected by either plunging a bottle to a given depth into the suspension or sampling from some taps along a given vertical (frequently the vertical in the middle of a tank wall, Figure 1).

The ideal condition is that after the mixing a constant sediment concentration C_i is observed in each i point of the suspension (complete mixing) and that C_i can be measured from each tap along a given axial vertical during the sampling time. In this ideal case, the concentration profile along the vertical is uniform (Figure 1) and the mean concentration C_m , which is equal to the local concentration C_i , allows direct calculation of the actual sediment amount stored in the tank. This also implies that a single sample taken at any point of the stored suspension is representative of the actual sediment amount.

The ideal condition does not occur because the manual sampling procedure determines an incomplete mixing condition and during the sampling time sedimentation phenomena take place within the suspension. As a consequence, the concentration profile is not uniform and is characterized by increasing C_i values going from the surface to the bottom of the suspension (Figure 1). Both factors (incomplete mixing, sampling duration) suggest that the mean C_m concentration, obtained by integrating the vertical concentration profile, could not be representative of the actual concentration C of the suspension into the tank. The uncertainties obviously increase if a single sample is used for estimating C .

Calculating the mean concentration C_m from the measured C_i values implies the choice of a concentration profile shape. The simplest one assumes a linear concentration variation between two subsequent measurement points.

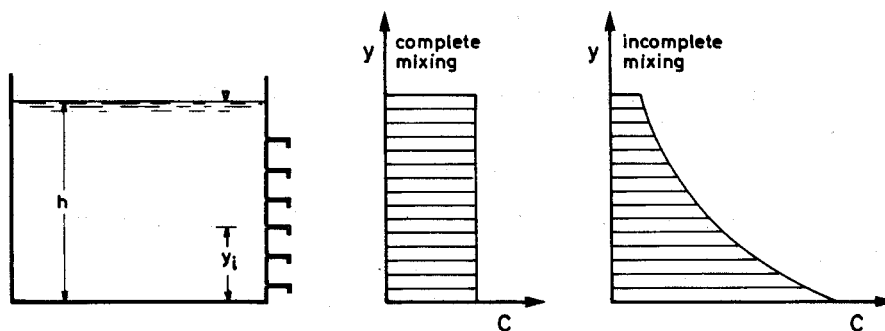


Figure 1. Diagram of a storage tank for soil loss measurement and typical concentration profiles

Hurst (1929) and Rouse (1938) experimentally investigated the concentration distribution in a vertical cylinder in which a lattice structure mixed a suspension of water and sand having a diameter ranging from 0.03 mm to 0.9 mm. The experiments by both investigators demonstrated that the concentration profile has the following mathematical shape (Graf, 1984):

$$\frac{C_i}{C_a} = \exp[b_o(y_i - a)] \quad (1)$$

in which C_i is the measured concentration at a distance y_i from the tank bottom; C_a is the reference concentration at the distance $y_i = a$ chosen nearest to the tank bottom; $b_o = -w/\epsilon_s$ in which w is the particle settling velocity and ϵ_s is the diffusion coefficient of the soil particles. Equation 1 is obtained by integrating the differential equation of diffusion by assuming a steady-state condition and a constant diffusion coefficient of the soil particles. Experiments by Hurst (1929) and Rouse (1938) also showed that the agreement was not quite perfect for larger particles. As a consequence, Equation 1 should be more useful for describing measured concentration profiles for clay suspensions rather than for sandy ones.

Independently of the choice of the theoretical profile, the incomplete mixing condition due to the manual sampling procedure suggests the need to determine a relationship, which will be termed the calibration curve, between the actual concentration C and the mean concentration C_m .

For a tank having a square plane, with a side length L (m), which is filled up to a height h (m) (Figure 1) with a suspension having an actual concentration C (kg m^{-3}), the mixing phenomenon is expressed by the following functional relationship:

$$f(C_i, C, x, y, z, h, L, g, \mu, \gamma, \gamma_s, d) = 0 \quad (2)$$

in which f is a functional symbol, x (m), y (m) and z (m) are the coordinates ($y-z$ is the plane reported in Figure 1), g (m s^{-2}) is acceleration due to gravity, μ (kg s m^{-2}) is water viscosity, γ (kg m^{-3}) is water specific weight, γ_s (kg m^{-3}) is soil particle specific weight, and d (m) is the particle diameter. If the suspension is sampled on a given tank wall ($x=0$, Figure 1) and along its axial vertical ($z=L/2$), and taking into account that μ and d can be joined into the settling velocity w (m s^{-1}), of particles (Graf, 1984), Equation 2 becomes:

$$f'(C_i, C, y, h, L, g, \gamma, \gamma_s, w) = 0 \quad (3)$$

in which f' is a functional symbol.

Since the functional relationship (Equation 3) represents a physical phenomenon that does not depend on the choice of measurement units, according to the Π -theorem of the dimensional analysis (Barenblatt, 1987) Equation 3 can be expressed using six dimensionless groups Π_i ($i=1$ to 6):

$$\phi(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6) = 0 \quad (4)$$

in which ϕ is a functional symbol.

In particular, using the variables C , h and w as dimensionally independent, the Π_1 group is determined by the following relationship:

$$\Pi_1 = C^\delta h^\beta w^\alpha C_i \quad (5)$$

in which δ , β and α are numerical constants. Substituting in Equation 5 the measurement units of each variable, the following equation is obtained:

$$\Pi_1 = \text{kg}^\delta \text{m}^{-3\delta} \text{m}^\beta \text{m}^{\alpha_s - \alpha} \text{kg m}^{-3} \quad (6)$$

Since Π_1 group is dimensionless, the numerical values of δ , β and α have to be derived solving the system of three equations deriving from Equation 6. Following the above-mentioned procedure, Equation 4 becomes:

$$\phi\left(\frac{C_i}{C}, \frac{y}{h}, \frac{L}{h}, \frac{gh}{w^2}, \frac{\gamma}{C}, \frac{\gamma_s}{C}\right) = 0 \quad (7)$$

which can be rewritten in the following explicit form:

$$\frac{C_i}{C} = \phi_1\left(\frac{y}{h}, \frac{L}{h}, \frac{gh}{w^2}, \frac{\gamma_s}{\gamma}\right) \quad (8)$$

in which ϕ_1 is a functional symbol.

Equation 8 is also valid for C_m which is calculated by integrating the C_i values:

$$b = \frac{C_m}{C} = \phi_2\left(\frac{L}{h}, \frac{gh}{w^2}, \frac{\gamma_s}{\gamma}\right) \quad (9)$$

in which ϕ_2 is a functional symbol. For a tank having a known L value, for given tank water level h and soil, Equation 9 establishes that ratio b is a constant, i.e. the relationship between the measured mean concentration C_m and the actual one C , which will be termed the *calibration curve*, is linear.

For a given tank and soil type, Equation 9 becomes:

$$b = \frac{C_m}{C} = \phi\left(\frac{gh}{w^2}\right) \quad (10)$$

in which ϕ is a functional symbol, which establishes that the slope b of the calibration curve depends on the tank water level.

A phenomenon is defined as self-similar in a given dimensionless group when the functional relationship $\Pi_1 = \psi(\Pi_2, \Pi_3, \dots, \Pi_n)$, representing the physical phenomenon, is independent of Π_n . When the function ψ has a limit equal to zero or infinity, the phenomenon is expressed by the following functional relationship:

$$\Pi_1 = \Pi_n^\alpha \psi_1(\Pi_2, \Pi_3, \dots, \Pi_{n-1}) \quad (11)$$

in which ψ_1 is a functional symbol and α is a numerical constant. This instance is termed incomplete self-similarity in the parameter Π_n (Barenblatt, 1979, 1987; Ferro, 1997). Since the ψ function vanishes for $h \rightarrow 0$, the

phenomenon is incompletely self-similar with respect to gh/w^2 :

$$b = k \left(\frac{w^2}{gh} \right)^n \quad (12)$$

in which k and n are two numerical constants.

According to Equation 10, for each level h one experimental run (a pair (C_m, C)) would be sufficient to determine b ; according to Equation 12 two experimental runs (for two different levels) would be necessary to determine the functional relationship between b and h .

For tanks having different sizes (different L values), for a given soil type, Equation 9 becomes:

$$b = \varphi_2 \left(\frac{L}{h} \right) \quad (13)$$

in which φ_2 is a functional symbol. Since the φ function vanishes for $L \rightarrow 0$, the phenomenon is incomplete self-similar also with respect to L/h :

$$b = k_1 \left(\frac{L}{h} \right)^m \quad (14)$$

where k_1 and m are numerical constants which can be estimated by two experimental runs, carried out for two different levels in a tank of known side length L .

If the values of the two constants k_1 and m are determined using a small tank with a side length L_m , which will be named *model*, Equation 14 shows that the following *scale-up relationship* can be established with a prototype tank having a side length L_p :

$$\frac{b_p}{b_m} = \left(\frac{L_p}{L_m} \frac{h_m}{h_p} \right)^m \quad (15)$$

where h_p and h_m are the water levels in the prototype and model tanks, respectively, and b_p and b_m are the slopes of the corresponding calibration curves.

In conclusion, the scale-up relationship (Equation 15) allows the experimental investigation of other factors affecting the calibration curve (sampling direction along the vertical, representativeness of the calibration curve, sampling volume, mixing time, delay time, mathematical shape of the concentration profile) using a small model tank.

EXPERIMENTAL INSTALLATION AND TESTING PROCEDURE

In a semi-arid Mediterranean area of Sicily an experimental installation for plot soil erosion measurement was built (Bagarello *et al.*, 1996). The sampling device is a sequence of three tanks hydraulically connected by triangular weirs (Figure 2). Each tank has a volume of about 1 m^3 ($0.94 \text{ m} \times 0.94 \text{ m} \times 1.16 \text{ m}$) and is equipped with 10 taps installed along the axial vertical of a wall.

For calibrating a storage tank, these taps were installed with a constant spacing of 0.10 m. A sandy soil (S soil, Figure 3), a quasi-full ($h=1.06 \text{ m}$) tank and five actual concentrations, ranging from 8.5 to 173 g l^{-1} , were used to determine the calibration curve. In particular, for each C value, water and soil put into the tank were



Figure 2. Sequence of storage tanks

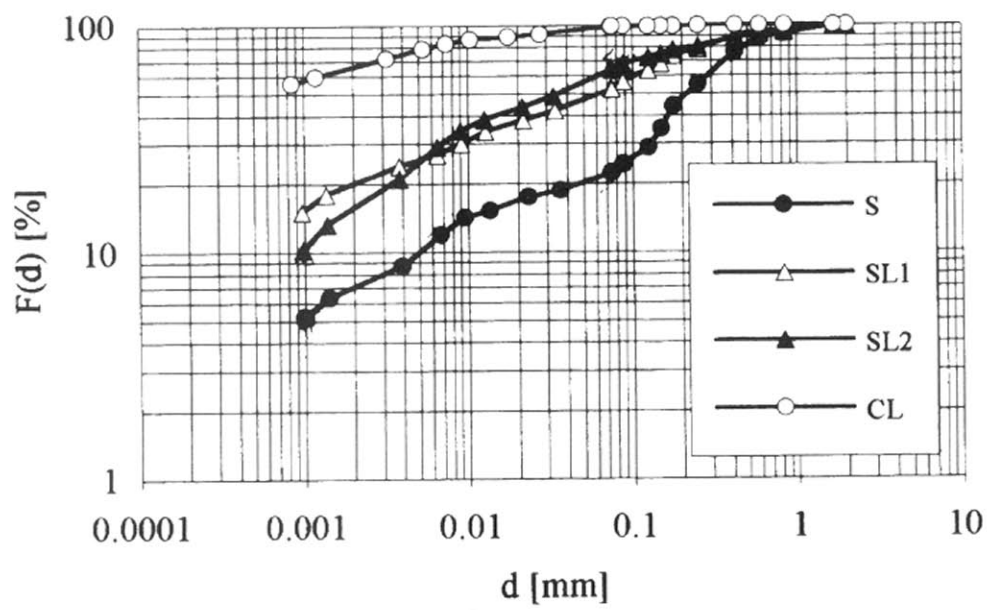


Figure 3. Particle size distribution of the investigated soils

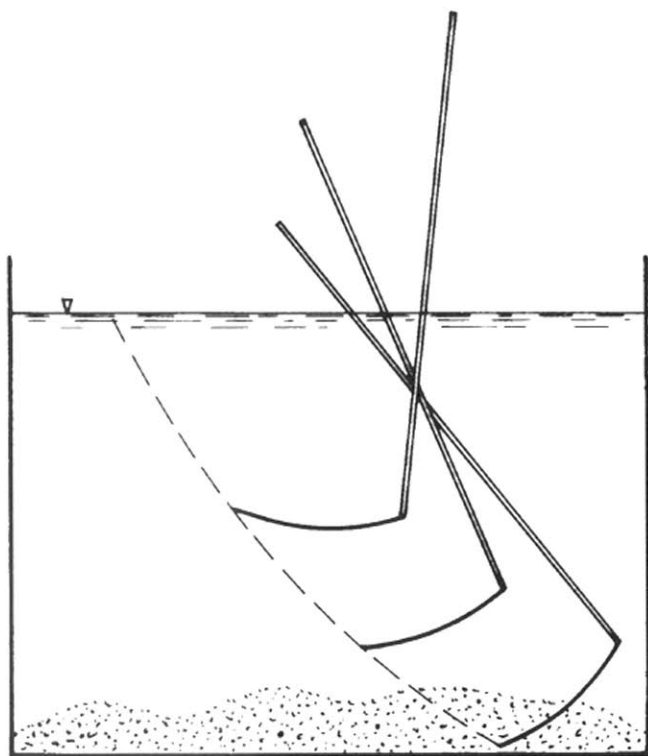


Figure 4. Diagram of the soil particles suspension method

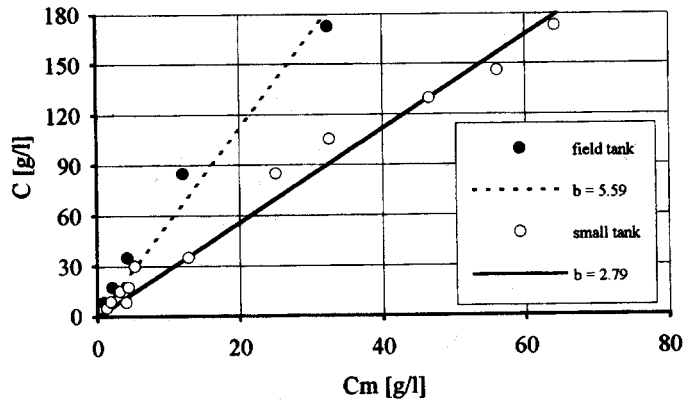


Figure 5. Calibration curve of the field and the small tank

mixed for a given time t_m ($t_m = 15$ min) by a flat scoop, in order to suspend the soil particles from the tank bottom to the water surface (Figure 4). After the mixing, 10 suspension samples, each having a volume of 1.5 l, were taken starting from the upper tap. For each actual concentration, a linear concentration variation between two subsequent measurement points were assumed to calculate C_m . Figure 5 confirms that the relationship between the mean (C_m) and the actual (C) concentration is linear with a slope b equal to 5.59. As a matter of fact, coefficient b is very different from unity, confirming that the conditions of a poorly mixed suspension, the sampling duration, and the use of samples collected along a single vertical produced a calculated mean concentration less than the actual one. As a consequence, a calibration curve has to be determined to use a storage tank as a soil loss measurement device.

To investigate the influence of factors affecting the slope of the calibration curve, we first tested a small-scale model of the field storage tank. The laboratory tank has a volume of about 0.128 m^3 ($0.47 \text{ m} \times 0.47 \text{ m} \times 0.58 \text{ m}$) and is equipped with six taps having a spacing equal to 0.09 m and installed along the axial vertical of a wall. The same sandy soil S, a quasi-full ($h = 0.56 \text{ m}$) tank and eight actual concentrations, ranging from 5 to 173 g l^{-1} , were used to determine the calibration curve. For each C value, a mixing time equal to 15 min and a sampling volume of 0.5 l were used. Figure 5 also shows the comparison between the calibration curve, having a least squares estimate of the slope b equal to 2.79, of the small tank and the experimental points. For actual concentration values less than 35 g l^{-1} , Figure 5 also shows that the experimental points (C_m, C) of the small tank are near to experimental pairs (C_m, C) determined for the field tank. Taking into account that the small tank and the field tank are characterized by the same ratio L/h , this result agrees with the scale-up relationship (Equation 15) which would provide the same slope b of the two calibration curves. For C values greater than 35 g l^{-1} , the slope of the two calibration curves is noticeably different. This result can be justified taking into account that the mixing efficiency, the sampling procedure, the sedimentation phenomena, the tank volume, the sampling volume and other factors can strongly affect the measured C_m values.

Figure 5 shows that the experimental (C_m, C) data pairs have a noticeable scattering around the calibration curve, proving the need to use more than a single pair (C_m, C), as Equation 10 establishes, to estimate coefficient b .

To verify that the calibration curve is a straight line for given water depth and soil, for each of the four soil types, ranging from a sandy soil to a clayey one (Figure 3) which will be used in the following experimental investigation, the relationship between concentrations C and C_m was determined. Each run was carried out by a full tank (water depth h equal to 0.56 m), a mixing time, t_m , of 15 min, and a sampling volume $V = 0.5 \text{ l}$. For each soil, Figure 6 shows the comparison between the experimental pairs (C_m, C) and the linear calibration curve whose b values are listed in Table I. For each calibration curve, the determination coefficient r^2 and mean square error MSE are also listed in Table I. A linear calibration curve is generally adequate and useful for practical application even if the scattering of the experimental data, which is more appreciable for the sandy soil (Figure 6a), clearly confirms the need to perform a series of (C_m, C) measurements for establishing the calibration curve.

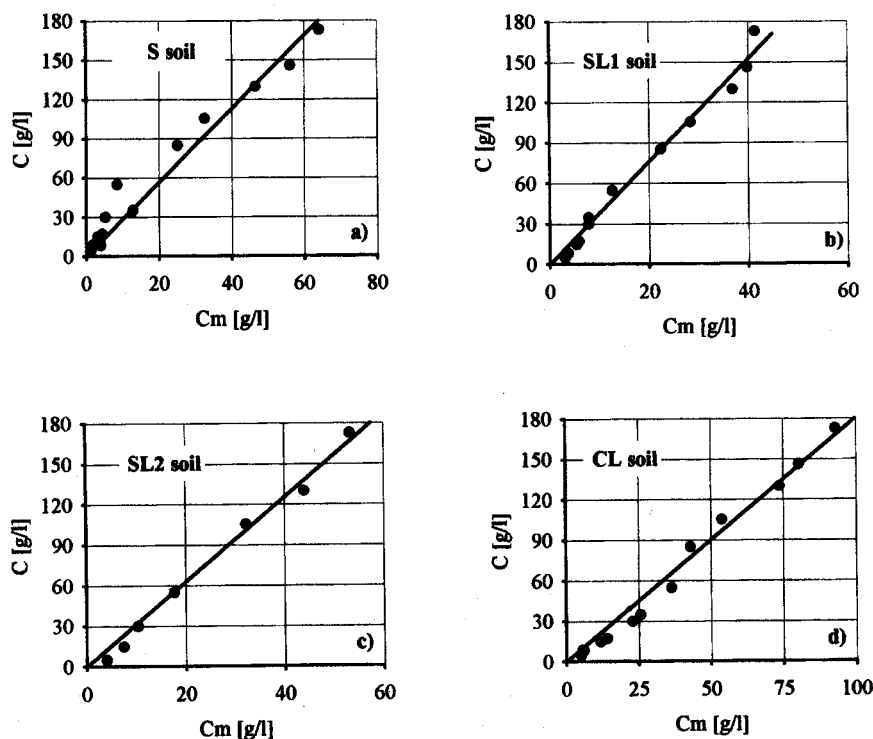


Figure 6. Calibration curves for the investigated soils

Table I. Statistical parameters of the calibration curves for different soil types

Soil	b	r^2	MSE
S	2.81	0.954	157.6
SL1	3.80	0.985	50.4
SL2	3.13	0.989	42.9
CL	1.80	0.984	54.8

In the following, the results of an experimental investigation, carried out for the different soil types of Figure 3, will be reported. The laboratory runs were carried out to investigate the influence on the calibration curve of the following factors: (1) sampling direction along the vertical, i.e. starting the sampling from the upper tap to the lower one or *vice versa*; (2) mathematical shape of the concentration profile; (3) representativeness of the calibration curve; (4) sampling volume; (5) water depth in the tank (i.e. filling level); (6) suspension mixing time; (7) grain size distribution of the eroded soil particles for given soil type; (8) time between the end of the erosive event and the start of the sampling procedure (delay time). Finally, the results of an attempt to define a simpler sampling procedure will be presented.

FACTORS AFFECTING THE CALIBRATION CURVE

Sampling direction along the vertical

To test the influence of the sampling direction along the vertical on the measured soil particle concentration profile, four runs were carried out for the clay soil (Figure 3) by using actual concentration C equal to 15 and 40 g l^{-1} . For each C value, after mixing the suspension, the sampling was performed starting from the upper tap to the lower one (up-down sampling) and *vice versa* (down-up sampling). Figure 7 compares the concentration profiles measured for each sampling direction. The up-down sampling procedure is characterized by

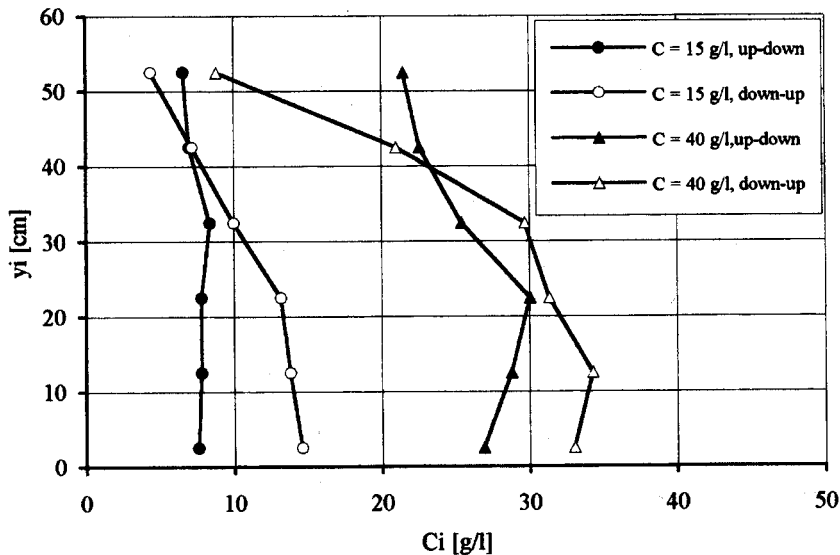


Figure 7. Comparison between the concentration profiles measured for the up-down and down-up sampling directions

concentration gradients lower than the ones corresponding to the down-up sampling. The concentration measured in the first tap is higher for the up-down sampling direction than for the opposite one because in the first case the sampling occurs just after mixing; in the second case the measured concentration is reduced for the suspension sedimentation processes which occur during the time spent for the sampling from the other taps. On the contrary, the bottom concentration is higher for the down-up procedure because the sampling is carried out from a well mixed suspension, while for the up-down sampling during the time between the end of mixing and sampling from the last tap sedimentation of coarser particles occurs.

In conclusion, for establishing the slope b of the calibration curve, a sampling direction has to be selected. In the following, the up-down procedure will be used because this sampling follows the sedimentation direction and produces a more uniform concentration profile.

Influence of the mathematical shape of the concentration profile

A theoretical mean concentration, $C_{m,t}$, is deduced integrating the concentration profile (Equation 1):

$$C_{m,t} = \frac{C_2}{b_o(h-a)} [\exp[b_o(h-a)] - 1] \quad (16)$$

For each actual concentration C , Equation 16 allows the corresponding measured concentration $C_{m,t}$ to be calculated and the slope b_1 of the calibration curve to be determined for given water depth and soil. Figure 8 shows, as an example for CL soil, a good agreement between the pairs $(C_{m,t}, C)$ and a linear calibration curve.

To test the influence of the concentration profile shape (linear, theoretical Equation 1) on the calibration curve, the experimental runs corresponding to SL1 and CL soil and to actual concentrations ranging from 5 to 172.8 g l⁻¹ were examined. Figure 9a-d, as an example for two actual concentration values (5 and 30 g l⁻¹), compares the pairs $(y_i - a, C_i/C_a)$ with the theoretical concentration profile. The agreement between experimental pairs and Equation 1 is better for the CL soil than for the SL1 one. This result can be explained taking into account that sedimentation processes during sampling are less important for finer particles (CL soil) than for coarser ones (SL1 soil). For increasing C_i values, which are measured in the points nearest to the tank bottom, the sedimentation and impact particle processes become more and more relevant. In other words, near

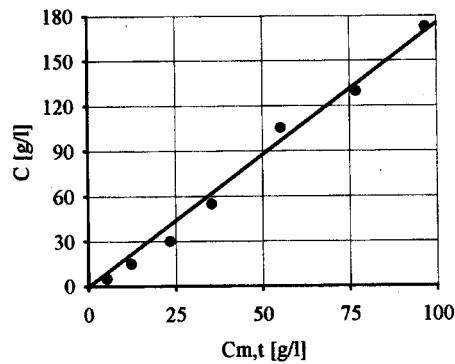


Figure 8. Calibration curve for the clay soil and assuming the theoretical concentration profile (Equation 1)

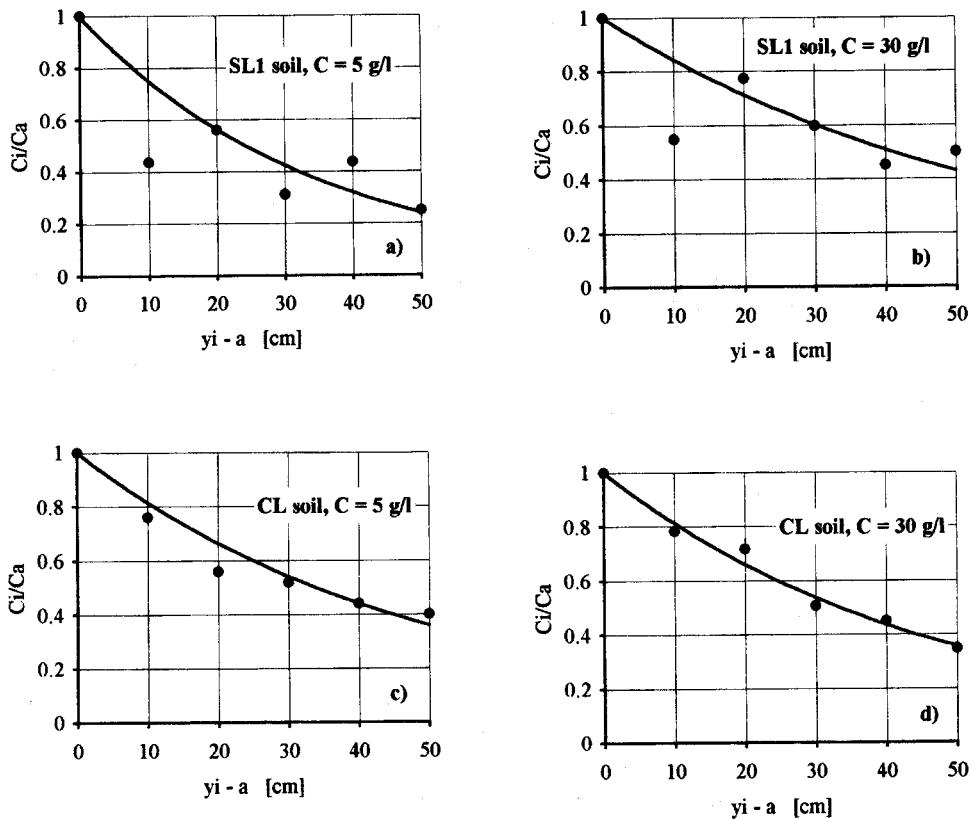


Figure 9. Comparison between the theoretical concentration profile (Equation 1) and the measured concentration values

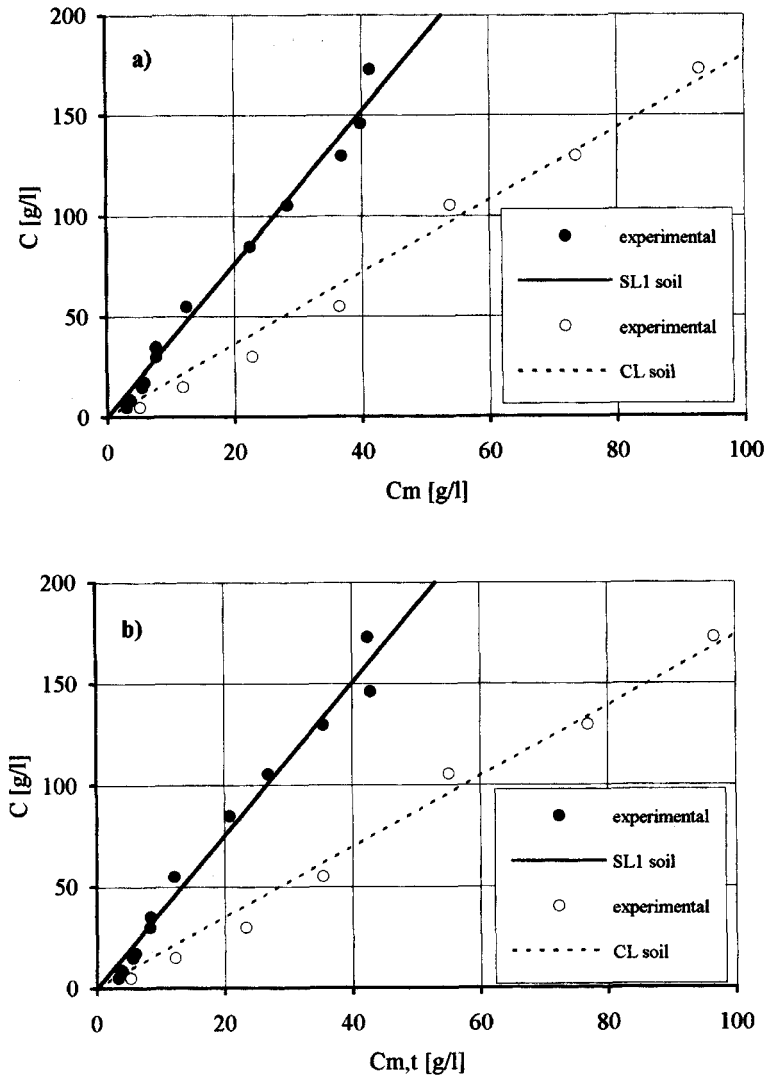


Figure 10. Comparison between the calibration curves corresponding to the linear (a) and the theoretical (b) mathematical shape of the concentration profile

Table II. Statistical parameters of the calibration curves of four different series of runs

Run	b	r^2	MSE
I	2.15	0.993	42.7
II	2.08	1.000	1.5
III	2.11	0.994	35.6
IV	2.07	0.996	22.0

the bottom of the tank the agreement between $(y_i - a, C_i/C_a)$ and Equation 1 is worse than near the water surface because the concentration values are so high that the diffusion scheme becomes inapplicable.

In conclusion, the theoretical-based profile is less adaptable for the higher concentration values measured near the bottom and its choice does not improve the accuracy of the tank calibration curve (Figure 10). On the

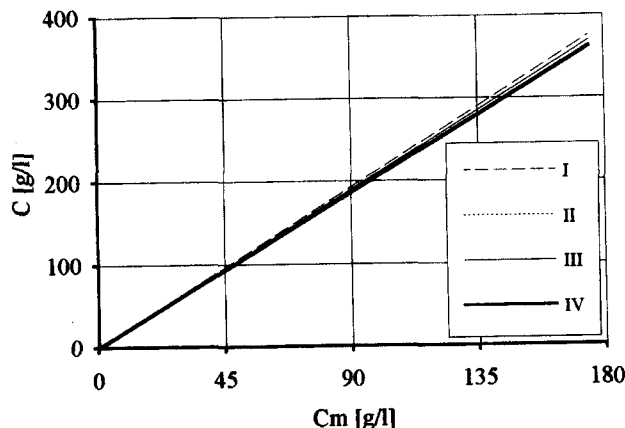


Figure 11. Comparison among the calibration curves of different series of runs

other hand, the simpler linear profile reproduces the measured C_i values and allows a calibration curve to be obtained which is as accurate as the previous one.

Representativeness of the calibration curve

To establish the number of run series useful for obtaining a representative calibration curve, the calibration curve was determined for the SL2 soil four times by using a homogeneous soil mass taken from a single site at the same time. Stones and crop residuals were removed from the soil mass. After oven-drying, the soil aggregates were broken into small particles. Each linear calibration curve was experimentally determined by four actual concentrations ($C=5, 30, 105.4$ and 172.8 g l^{-1}). Each run was carried out by a full tank, a mixing time of 15 min, and a sampling volume $V=0.51$.

Table II shows, for each series of runs, (I, II, III and IV), the coefficient b , the determination coefficient r^2 and mean square error MSE . Figure 11 compares the calibration curves corresponding to each series of runs. Both Table II and Figure 11 show negligible differences among the four replicates. To verify that the four calibration curves were not significantly different, the homogeneity of the residual variance of the four calibration curves was at first verified by Bartlett test; an F-test was then applied for establishing the parallelism among the four regression curves (Snedecor and Cochran, 1989). A 0.05 probability level was chosen for each test. The statistical analysis confirmed that the four series of runs gave calibration curves that were not statistically different and that a single b value equal to 2.10 can be used for the investigated soil. As a consequence, the analysis showed that a calibration curve obtained from a single series of runs adequately describes the relationship between the mean and the actual concentration. In other words, the same operator repeating the same experimental procedure a given number of times is able to determine the same calibration curve (repeatability of the calibration procedure).

Influence of the sampling volume

For studying the influence of the sampling volume on the calibration procedure, two series of tests were carried out for two soils (SL1 and CL of Figure 3) and two sampling volumes V ($V=0.5$ and 1.51). For each test, $h=0.56 \text{ m}$ and $t_m=15 \text{ min}$ were used. Each calibration curve was determined for 13 actual concentrations ranging from 5 to 172.8 g l^{-1} . Figure 12 shows, for each investigated soil, the calibration curves corresponding to each sampling volume. For each actual concentration C , C_m values increase for decreasing V values. This result likely depends on the relationship between the sampling time and the used sampling volume; in fact, higher V values cause higher sampling times during which the suspended particle sedimentation is more relevant. Since the V influence on the b coefficient is noticeable, the sampling volume has to be considered as a constant parameter of the whole calibration procedure.

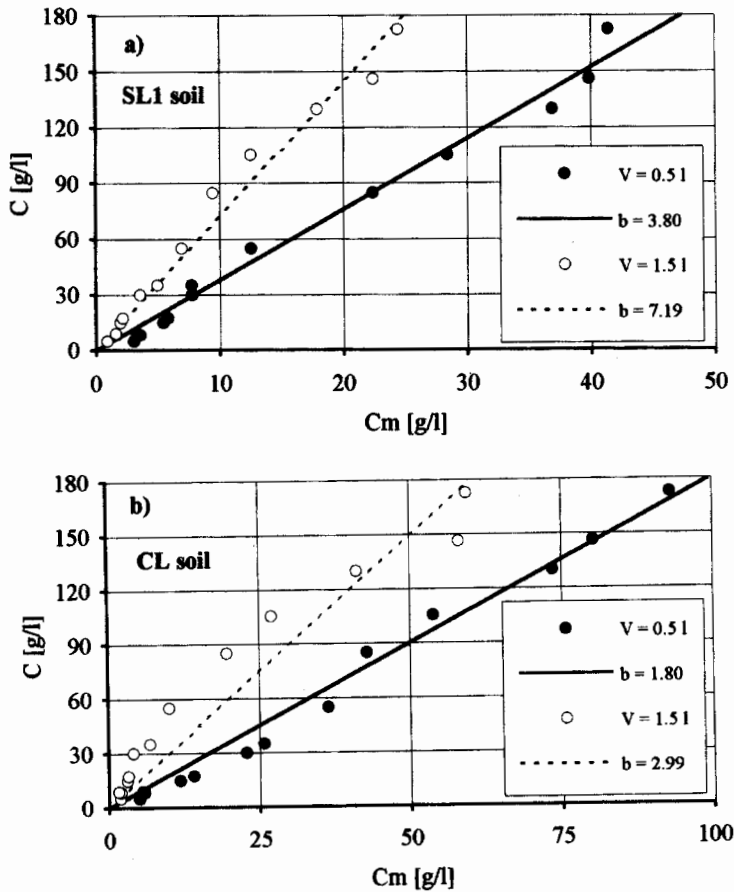


Figure 12. Calibration curves corresponding to different sampling volumes

Influence of the tank water level

Since in field conditions the complete filling of the tank is not always assured, we also verified whether the calibration curve is affected by the water depth h in the tank according to Equation 12. From a practical point of view, the water depth affects the number of taps usable for sampling operations and, as a consequence, the measured concentration profile used to calculate C_m . Three soils (S, SL2 and CL), a mixing time of 15 min and seven h values ranging from 0.14 to 0.56 m were used for this investigation. For each water depth, the calibration curve was obtained by experimental runs carried out for seven actual concentration values ranging from 5 to 172.8 g/l. For given soil type and water depth, the measurements confirmed that coefficient b is constant (linear calibration curve). Figure 13 shows that for each soil the $b(h)$ relationship assumes the mathematical form established by Equation 12. For each soil, Table III lists the k and n coefficients.

It should be noted that the C_m concentration is calculated by a concentration profile measured by a decreasing number of taps for decreasing water depth in the tank, and moreover a different mixing effectiveness corresponds to different water depths. In other words, two different effects, which always happen in the field, are lumped together.

Influence of the mixing time

The influence of the mixing time t_m was studied by determining the calibration curve for the CL soil, in the range $5 \leq C \leq 172.8$ g/l, corresponding to three t_m values ($t_m = 5, 10$ and 15 min). In each experimental run the tank was full. Figure 14 shows, for the CL soil and a mixing time equal to 5 min, that the linear calibration curve can still be applied. Since the same result was also obtained for the experimental pairs (C_m, C) corresponding to

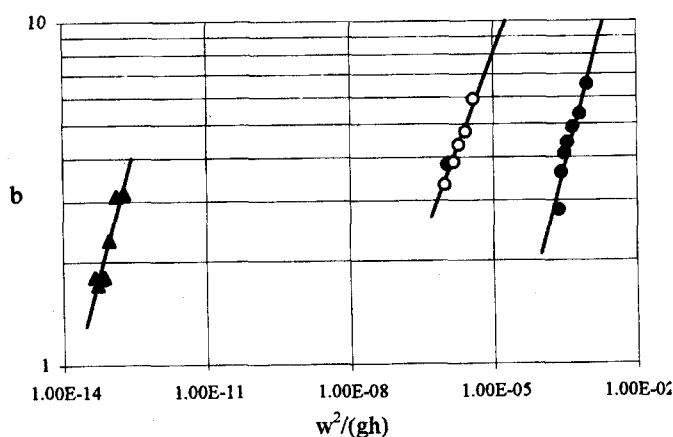


Figure 13. Relationship between coefficient b and the water depth for different soils

Table III. Coefficients k and m of equation 12 for each investigated soil

Soil	k	n
S	251.6	0.5203
SL2	531.8	0.3646
CL	10558319	0.5111

$t_m = 10$ min, we can conclude that the shape of the calibration curve is independent of the mixing time. For verifying whether coefficient b is also independent of t_m , the three regression lines were statistically compared. The analysis showed that the slope of the calibration curve corresponding to $t_m = 5$ min is significantly different from the other ones; on the contrary, b coefficients were not significantly different for mixing times equal to 10 and 15 min (Figure 15). The experimental results show that the suspension mixing efficiency increases when t_m increases from 5 to 10 min (decreasing b values) while the efficiency can be considered practically invariable when the mixing time increases up to 15 min. This result can probably be explained taking into account that for high t_m values the efficiency increase is balanced by the soil particle settling processes.

Influence of the input particle size distribution

According to Cogo *et al.* (1983), several factors affect the size distribution of primary particles and aggregates of an eroded soil (type of erosion processes, soil type, surface conditions, slope length and steepness, rainfall pattern and upslope deposition). These authors showed, for example, that the size distribution of eroded aggregates is strongly dependent on the tillage system under the absence of residue cover.

For a given soil type, to test the dependence of the calibration curve on the characteristics (size distribution, preliminary treatment) of the sediment entering the tank, proper experimental runs were carried out.

In particular, for the SL2 soil the tests were carried out using the following treatments: no altered soil (as taken in the field) (NAS); oven-dried soil passed through a 4.76 mm sieve (OD476); oven-dried soil passed through a 2.00 mm sieve (OD200); soil taken in the field with manual removal of rock fragments and crop residuals (MD). For the CL soil, the tests were carried out with the same soil taken from two neighbouring experimental sites (S1, S2) and the eroded sediment stored in a field tank (ES). A full tank, a mixing time equal to 15 min and concentrations up to 172.8 g l^{-1} were used.

Figure 16 shows, for the SL2 soil, the comparison between the calibration curves corresponding to the treatments NAS, OD476, OD200 and MD. The analysis showed that the calibration curves corresponding to

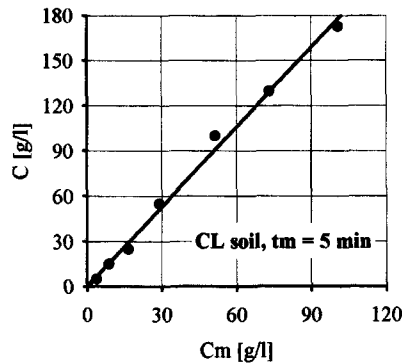


Figure 14. Calibration curve for the CL soil corresponding to a mixing time equal to 5 min

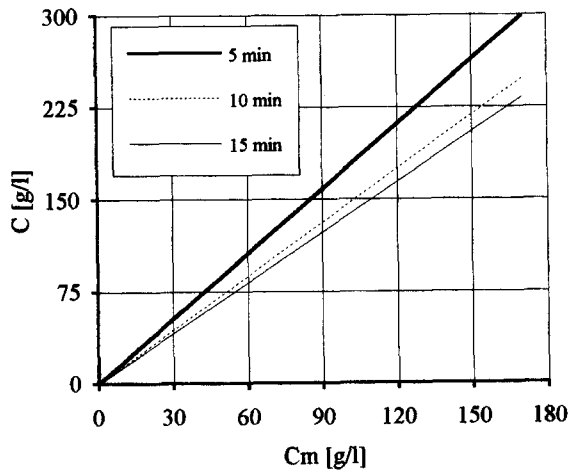


Figure 15. Comparison of calibration curves corresponding to different mixing times

different treatments coincide statistically. Figure 17 and the results of the statistical analysis show that, for the CL soil also, the calibration curves corresponding to the different sediment sources are not significantly different.

Influence of the delay time

All experiments previously described were carried out by putting the soil into the tank and sampling immediately after the soil suspension mixing. For field applications, this procedure corresponds to a sampling performed immediately after the end of the erosive event.

To test the effect of the delay time d_t , i.e. the time between the end of the erosive event and the start of the sampling procedure, the CL soil and an actual concentration equal to 25 g l^{-1} were used. First, a cylindrical test tube was used to visualize the sedimentation process of the selected soil. The test showed that most soil particles settled after one hour. Figure 18 shows the measured C_m concentrations for each selected delay time ($d_t = 0, 1, 2, 3, 4, 5, 6, 12, 24$ and 48 h). Each C_m value was measured after filling the tank with clear water, putting the soil into the tank, and mixing for 5 min after the selected delay time. With the exception of the concentration measured at $d_t = 0$, which is affected by the input process of the soil into the tank, the C_m values are practically unaffected by the delay time; as a consequence, the scattering around the mean value of the concentration values measured for $d_t > 0$ (16.2 g l^{-1}) is attributable to experimental errors. This result agrees with the observed

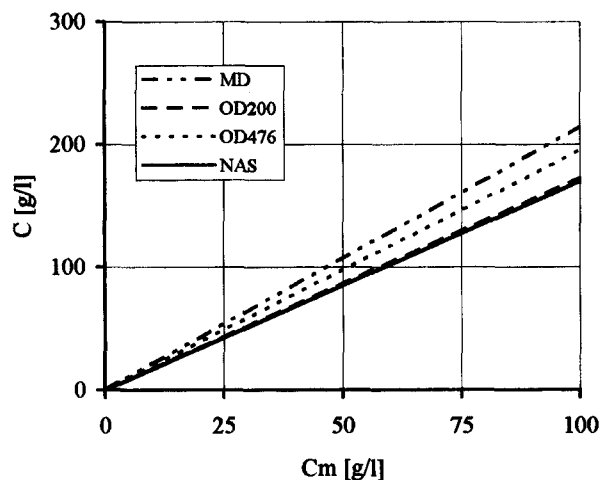


Figure 16. Comparison of calibration curves corresponding to different treatments of the SL2 soil

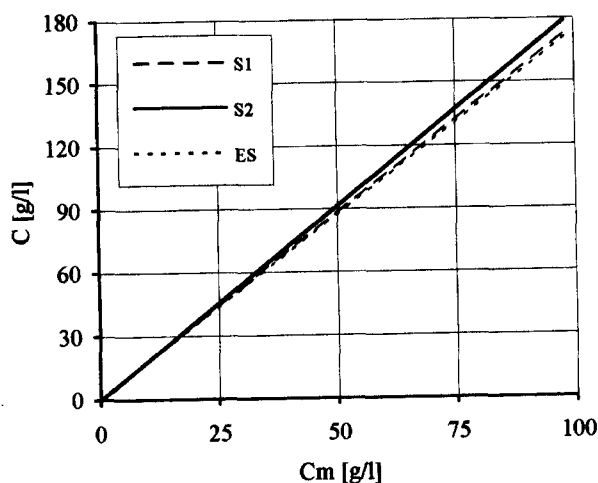


Figure 17. Comparison of calibration curves corresponding to different sediment sources of the CL soil

settling process in the cylindrical test tube; all the delay times greater than 1 h determine the same initial condition for mixing.

Simplified sampling procedure

According to Equation 8, a single suspension sample can be used to calibrate a storage tank. A similar sampling procedure was tested by Lang (1992) who observed a linear relationship between the bottom concentration measured by a bottle sampler and the actual concentration.

Two different sampling procedures were used in this work: (1) the calibration curve was established by relating the actual concentration to the measured one C_b by the tap nearest to the tank bottom only; (2) the relationship between C and the measured bottom concentration C_{bt} was determined by a single sample carried out by a bottle dipped into the tank.

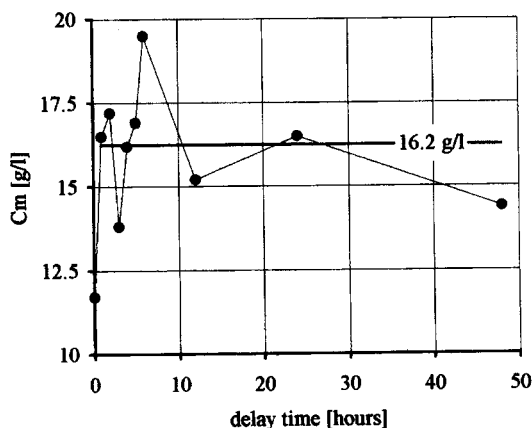


Figure 18. Relationship between the measured mean concentration values and the delay time

For testing the first procedure, 10 experimental runs were carried out in the full tank by using the CL soil and actual concentration values ranging from 2 to 40 g l^{-1} . For each actual concentration, after mixing, the sampling from the lowest tap and the up-down procedure were started at the same time. The comparison between the calibration curves $C-C_b$ and $C-C_m$ is plotted in Figure 19. Although both calibration curves are linear, as expected according to Equation 8, a more noticeable scattering characterizes the $C-C_b$ relationship. In other words, the calibration curve $C-C_b$ gives an actual concentration estimate which is less accurate than the calibration curve deduced by using a mean concentration calculated by a measured profile.

The sampling procedure using a bottle was carried out by dipping a bottle having a volume equal to 0.5 l into the mixed suspension. The bottle was kept closed until reaching the tank bottom and was then opened to allow sampling (Figure 20)

Figure 21 shows that the calibration curve can be represented by a straight line, further confirming the applicability of Equation 8, and that the slope b depends on the water depth in the tank, as established by Equation 10:

$$C = b C_{bt} \quad (17)$$

It should be noted that the scattering of the experimental data pairs (C_{bt}, C) around the regression line is comparable to the scattering of the couples (C_m, C) around the corresponding calibration curve (Equation 9). In other words, the accuracy of estimating C by Equation 17 is comparable to that achievable by Equation 9.

CONCLUSIONS

In this paper, an investigation was carried out to examine different factors affecting the manual sampling procedure for measuring the suspended sediment concentration in a runoff-soil loss storage tank.

At first, using the II-theorem of the dimensional analysis, the functional relationship describing the mixing of the suspension into the tank was expressed in a dimensionless form. The recognized dimensionless groups allowed to establish that for a given soil and water depth in the tank, the relationship between the actual and the measured concentration (calibration curve) is linear. For a given soil, the slope of the calibration curve is related to the water depth. The same dimensionless groups allowed scale-up procedure to be deduced and enabled the use of a small tank, similar to the field one, for investigating additional effects (mathematical shape of the concentration profile, sampling direction along the vertical, representativeness of a calibration curve, mixing time, etc.) neglected in the theoretical analysis.

In particular, the effects of the following factors were examined: (1) sampling direction along the vertical; (2) mathematical shape of the concentration profile; (3) representativeness of the calibration curve; (4) sampling volume; (5) water depth into the tank; (6) suspension mixing time; (7) grain size distribution of the eroded soil

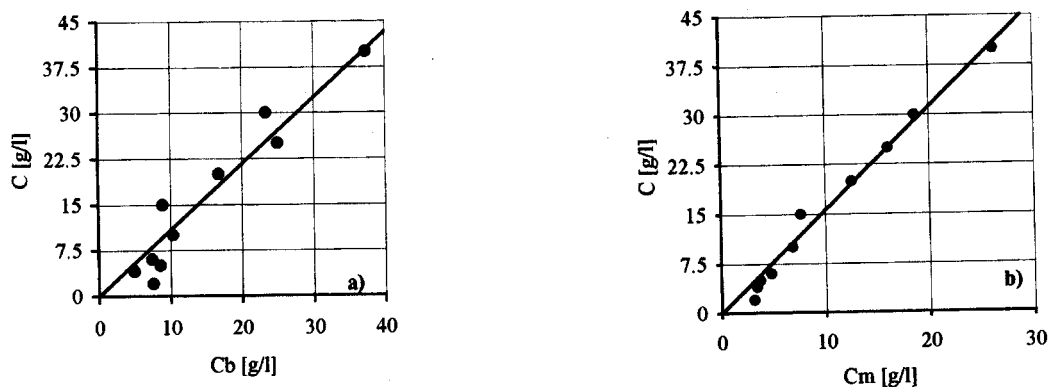


Figure 19. Comparison between the $C-C_b$ (a) and $C-C_m$ (b) relationship for the CL soil

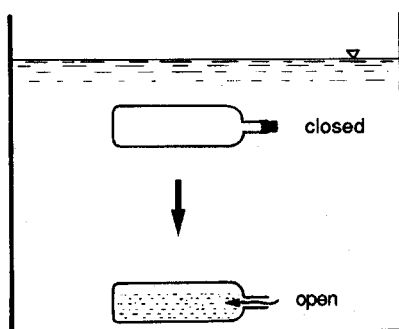


Figure 20. Operating scheme of the bottle dipping into the tank to collect the sample

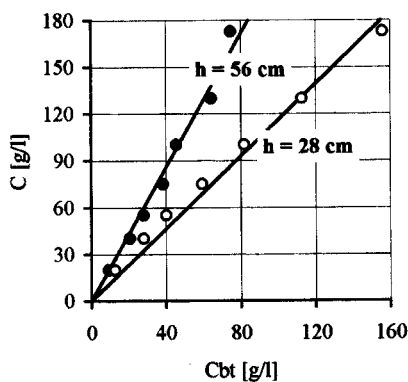


Figure 21. Calibration curve for the CL soil obtained by using the bottom concentration measured by a bottle dipped into the tank

particles for given soil type; (8) time between the end of the erosive event and the start of the sampling procedure.

The experimental runs showed that the up-down sampling procedure was characterized by measured concentration gradients lower than the ones corresponding to the down-up sampling because an interference between the sedimentation processes during the sampling time and the chosen sampling sequence occurs.

Therefore for establishing the linear calibration curve, a sampling direction has to be selected. The up-down procedure which follows the sedimentation direction and produces a more uniform concentration profile appears to be preferable.

The analysis also showed that the theoretically based profile (Equation 1), obtained by integrating the differential equation of diffusion, was less adaptable for the higher concentration values measured near the bottom and its choice did not improve the accuracy of the tank calibration curve, compared to that obtained by assuming a linear variation between two measurement points.

A calibration curve obtained from a single series of runs adequately described the relationship between the mean and the actual concentration. In other words, the same operator repeating the same experimental procedure a given number of times should be able to determine the same calibration curve.

A noticeable influence of the sampling volume on the slope of the calibration curve $C-C_m$ was recognized; as a consequence the sampling volume has to be considered as a constant parameter of the whole calibration procedure.

Since in field conditions the complete filling of the tank is not always assured, the relationship between the degree of filling and the slope of the calibration curve was studied. A significant influence of the water depth in the tank on the calibration curve, as established by theoretical analysis, was also recognised experimentally.

The experimental results showed that the suspension mixing efficiency increases when the mixing time t_m increases from 5 to 10 min while the efficiency can be considered practically invariable when the mixing time increases up to 15 min. Therefore specific calibration curves have to be deduced for short durations ($t_m < 10$ min) of mixing time.

The dependence of the calibration curve on the characteristics (size distribution, preliminary treatment) of the sediment entering the tank was examined. In all examined cases the analysis showed that the calibration curves corresponding to different treatments were not statistically different.

The effect of the time between the end of the erosive event and the start of the sampling procedure (delay time) was tested. All delay times greater than 1 h determined the same initial condition for mixing.

Finally, an attempt to define a simpler sampling procedure was carried out. The calibration curve was first established by relating the actual concentration to the measured one C_b by the tap nearest to the tank bottom only. This calibration curve $C-C_b$ was less accurate than the one deduced by using a mean concentration calculated by a measured profile. A further sequence of runs showed that for improving the accuracy of the calibration curve based on a single measurement, a different sampling procedure using a dipped sampler should be used.

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